# OPTIMIZATION OF PARTICLE ACCELERATORS (OPAC)*

C.P. Welsch[#], Cockcroft Institute and The University of Liverpool, UK


*Abstract*

The optimization of the performance of any particle accelerator critically depends on an in-depth understanding of the beam dynamics, powerful simulation tools and beam diagnostics, as well as a control and data acquisition system that links all the above. The oPAC consortium has carried out collaborative research into these areas, with the aim to optimize the performance of present and future accelerators that lie at the heart of many research infrastructures. The network brought together research centers, universities, and industry partners to jointly train 23 researchers**.** This paper presents selected research outcomes from the network's scientific work packages, including results from beam dynamics simulations into upgrade scenarios for the LHC and 3rd generation light source ALBA, as well as initial results from a cryogenic current comparator for low intensity ion beams. Finally, it is shown how an open source control system based on a relational database using a dynamic library loader can help enhance overall facility performance.


## INTRODUCTION

The optimization of the performance of particle accelerators was the goal of the Marie Curie Initial Training Network (ITN) oPAC [1]. The project received 6 M€ of funding from the European Union within the 7th Framework Programme, making it the largest-ever ITN. It successfully trained 23 Fellows across 4 scientific work packages (WPs) and allowed them to develop expert knowledge in a number of different fields, such as engineering, physics, electronics, IT and material sciences. Training through network-wide events including schools and topical workshop, participation in international conferences, and secondments for specific skill-building has allowed them to carry out cutting edge research whilst providing them with a broad set of skills that is expected to be an excellent basis for their future careers.

## RESEARCH

The results from the oPAC Fellows' research have resulted in more than 100 contributions to international conferences and workshops. More than 30 papers have already been published in peer-reviewed journals and several more are currently in preparation as results from research projects are being analyzed and Fellows are finalizing their doctoral theses. The following sections present the results from selected research projects.

### *Beam Physics*

In this work package (WP) the Fellows have developed beam handling techniques and carried out detailed studies into the beam dynamics of several specific particle beams and machines. This has driven R&D also in the other WPs, as these developments are closely linked to new diagnostics, control systems and beyond state-of-the-art simulation tools. Several projects within this WP addressed upgrade studies of the Large Hadron Collider. This has required the development of numerical approaches that allowed assessing the impact of any change to the accelerator lattice on the final performance in terms of beam stability, likely losses and achievable luminosity. The different network events and in particular the Topical Workshop on the 'Grand Challenges in Accelerator Optimization' [2] where a whole session was dedicated to these studies allowed for critical review of all simulation results. A detailed study into the interaction region design for the LHeC was recently published [3]. The aim of this design was to achieve head-on electron-proton collisions in the interaction region 2 (IR2) at a luminosity of $L=10^{.}33cm^{-2}s^{-1}$ which requires a low $\beta^*=10$ cm. This was achieved by implementing a new set of quadrupoles closer to the interaction point, called the inner triplet (IT), at a distance L* from the IP. The flexibility of this design was studied in terms of minimizing $\beta^*$ to study the reach in luminosity, and in terms of increasing L* to reduce the synchrotron radiation. This work explored the different types of chromatic corrections for the nominal case with $\beta^*=10$ cm and L*=10 m by studying its impact on the stability of the beam via the dynamic aperture and the effect of non linearities via frequency map analysis. Three different chromatic corrections were studied. The first one, named "LHC-like" performs the chromatic correction similar to the LHC by changing the focusing and defocusing families by the same amount. The second correction, named the "LHeC-like" adds a further constraint to control the Montague functions in the collimation insertions and allows each sextupole family to change by a different amount. And finally, the third one contemplates correcting the second order chromaticity. DA studies were computed by E. Cruz from the Cockcroft Institute/University of Liverpool for the three chromatic correction schemes in SixTrack using a polar grid of initial conditions with 30 particles for each 2σ interval and 5 different phase angle, over $10^5$ turns. The momentum offset was set to $2.7\times10^4$. Concerning the magnetic errors, 60 different realizations (seeds) were considered for the LHC magnets. Results show a similar behavior at small angles for all three cases. On the other hand it was observed that at bigger angles the second order correction gives a bigger dynamic aperture for angles ~75°, although not that different from the LHeC-

*This project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no 289485.
#c.p.welsch@liverpool.ac.uk

like correction, while the LHC-like correction shows a negative impact for angles >50°. Frequency map analysis studies were then performed in SUSSIX and applied to calculate the variation in tunes over 5,000 and 10,000 turns for a sample of initial amplitudes via the diffusion factor. Similarities were again found for the LHeC-like and second order correction, except for the stable region observed at Qx ~Qy, where the latter case presents better results. Also, for bigger angles (Ix=0-5 σ and Iy ~20 σ) where the second order correction does not show the instability region observed in the LHeC-like case caused by resonance line (-1,4). The same regions are also different for the LHC-Like case. In this scenario the region for larger angles shows a higher instability, but the main difference is observed in the region with Qx ~Qy in which a stable region seen in the other corrections is no longer present, see Fig. 1.

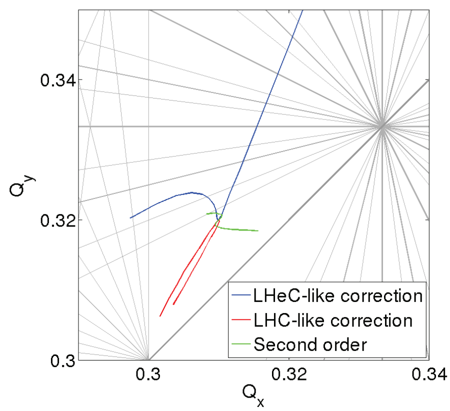


Figure 1: Calculated variation in horizontal and vertical tune for different corrections.

Fellow M. Carla who was based at the synchrotron ALBA in Spain studied ways to improve the knowledge and understanding of the nonlinear beam dynamics of synchrotron light sources through simulations, beam measurements and lattice optimization. He implemented a beam position monitor turn-by-turn technique for the first time in the ALBA synchrotron light source, providing a new tool to characterize the optics of the machine. By analyzing the spectra of turn-by-turn oscillations excited by a fast kicker magnet, it was possible to observe the resonant driving terms produced by the linear and nonlinear optics of the storage ring. Subsequently, the machine model has been adapted to reproduce the observed resonant driving terms and provide a map of the optics errors in the storage ring. Furthermore, the turn-by-turn technique has been applied to the measurements of the machine transverse impedance. The phase advance between BPMs was calculated and compared against the one expected from LOCO, see Fig. 2. In particular, it was found that the electromagnetic interaction of the stored electrons with the vacuum vessel results in a defocusing effect similar to the one produced by a common defocusing quadrupole. Thus a precise determination of the machine optics has been exploited to evaluate the contribution of the different accelerator sections to the impedance budget [4].

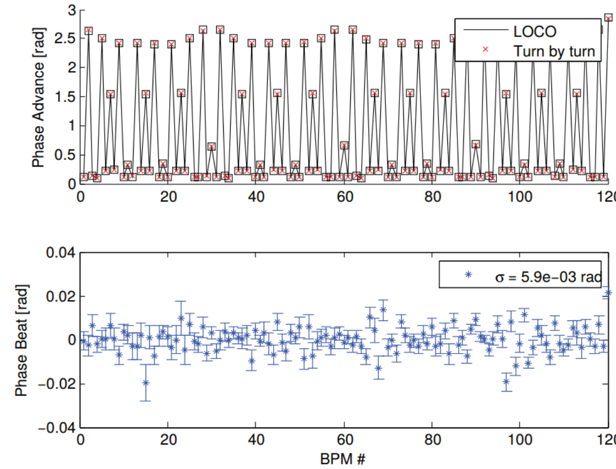


Figure 2: Top: Alba horizontal phase advance turn-by-turn measurements averaged over 100 kicks compared against the estimation from LOCO. Bottom: Phase beat and standard deviation. The error bars represent the reproducibility of the measurements, obtained from the standard deviation of the phase beat over 100 acquisitions.

## *Beam Diagnostics*

The developments in this WP received additional support by a dedicated hands-on training day in beam instrumentation hosted by Bergoz in June 2013. This familiarized all Fellows in the first year of their project with the particular challenges in carrying out measurements of the detailed characteristics of charged particle beams and allowed them to discuss progress in all sub projects. Of particular importance for instrumentation development is that no single monitor has yet been developed that is able to monitor all properties of a beam, i.e. several different technologies usually need to be combined to get a full understanding of the beam inside its vacuum chamber. Most oPAC projects initially targeted the development of a single detector (prototype) for a specialized purpose. Information from this monitor was then combined with other detectors and linked to the accelerator control and data acquisition system to obtain a full understanding about the beam. Moreover, several projects e.g. the one targeting absolute beam current measurement using a CCC [5], beam loss monitoring using cryogenic detectors [6], and transverse profile monitoring using ionization profile monitors [7] all target non-invasive beam monitoring. In combination, these monitors are excellent candidate technologies for a fully online beam monitor that would be able to measure all important parameters of a charged particle beam in a non-destructive way. Research progress in this WP has been excellent. This is reflected in large number of conference proceedings from contributions to IPAC and IBIC conferences, including contributed talks about high resolution profile measurements (K. Kruchinin), ALBA beam diagnostics systems (L. Torino), and the installation of beam positioning monitors (M. Cargnelutti). A two day


ISBN 978-3-95450-147-2

workshop on beam diagnostics was hosted by CIVIDEC in Vienna, Austria in May 2014 [8] and helped Fellows combine their research findings in view of an overall optimization of an accelerator diagnostics system. Two examples from research projects shall exemplify the achievements to date.

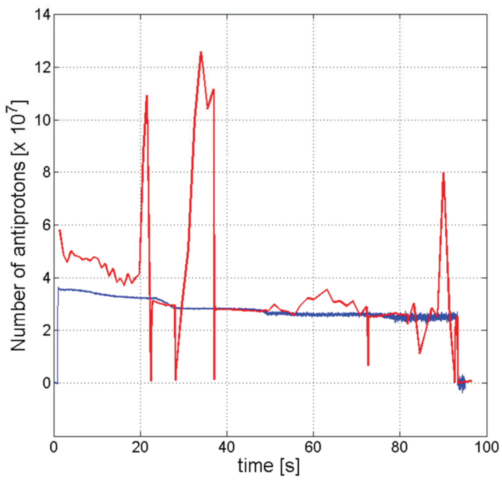


Figure 3: Comparison between measurement with Schottky noise based monitor (in red) and CCC (blue).

A Cryogenic Current Comparator (CCC) monitor optimized for the AD and ELENA rings at CERN has been developed by M. Fernandes, based at CERN, and first measurements with beam have been carried out, see Fig. 3 [9]. These are the first CCC beam current measurements performed in a synchrotron using both, coasting and short-bunched beams. The CCC is currently the only device able to measure non-perturbatively very low-beam intensities. A particular improvement is the possibility of absolute calibration of the experiments receiving the particle beam using data from the CCC, as well as cross-calibration of other intensity monitors for which no simple calibration method is available. A current intensity resolution of 30 nA was successfully demonstrated after low-pass filtering with a cut-off frequency at 10 Hz. The system was able to cope with a beam current signal slew-rate exceeding 8 kA/s maintaining the SQUID/FLL stability. A new cryostat mechanical design provided for an excellent decoupling of mechanical perturbations, enabling the CCC monitor to attain this performance even when the connected cryocooler unit was operating.

A laserwire emittance scanner has also been developed within oPAC in close collaboration with M. Kruchinin and Fellow T. Hoffmann from the LA$^3$NET project [10, 11]. In a first step simulations were conducted to determine the key parameters for laser and detector subsystems. After characterization of the identified components, a prototype system was designed and installed at the LINAC4 3 MeV test bench. In comparison to conventional systems for emittance measurement, the laserwire system has major advantages. Because of its principle, space charge perturbations for example are excluded. Its range of application starts at beam energies of MeV and reaches beyond Multi-GeV. Since no mechanical parts intercept the beam, it is a reliable and fully nondestructive method. The chosen laser system with kilohertz pulse repetition rate allowed to probe the emittance value of the $H^-$ beam pulse with microsecond resolution. The fiber-based laser system increased the reliability of the laser transport system and reduced greatly its complexity.

### *Simulation Tools*

WP4 focused on the development of new simulation tools. This WP was hence different in nature to the others as improvements in computational tools benefit all other developments in parallel. Research focused on enhancing the CST Particle Studio code with regards to GPU capability and the implementation of the Multi Level Fast Multipole Method (MLFMM) as a fast electromagnetic field solver. Given the central role of CST Particle Studio in the accelerator community a dedicated training day was hosted by CST AG at CERN in June 2013. This made all Fellows aware of the opportunities this simulation suite offers and of the developments within oPAC. Furthermore, a Topical Workshop in March 2015 was devoted to Computer-Aided Optimization of Accelerators [12].

### *Control and Data Acquisition Systems*

In an experimental physics facility containing numerous instruments, it is advantageous to reduce the amount of effort and repetitive work needed for changing the control system (CS) configuration: adding new devices, moving instruments from beamline to beamline, etc. In a project at COSYLAB, P. Maslov developed a versatile CS configuration tool which provides an easy-to-use interface for quick configuration of an entire facility. It relies on Microsoft Excel as frontend application and allows the user to quickly generate and deploy Input/Output Controller (IOC) configurations such as EPICS start-up scripts, alarms, and archive configurations onto IOCs. The Device Control Database (DCDB) tool uses a relational database, which stores information about all the elements of an accelerator. The communication between the client, database and IOCs is then realized by a REST server written in Python. The key feature of the DCDB tool is that the user does not need to recompile the source code. It is achieved by using a dynamic library loader, which automatically loads and links device support libraries.

## SUMMARY

oPAC has successfully trained 23 early stage researchers between 2012 and 2016. The network has also organized a large number of international schools and topical workshops that have benefited the world-wide accelerator community. On the basis of the extremely positive feedback that was received from the community, the consortium has decided to continue its communication and event organization activities for at least one more year.

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ISBN 978-3-95450-147-2